

# Higgs assisted electroweak-ino production

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# Outline

- Introduction
- Naturalness in Supersymmetry
- SUSY electroweak searches at the LHC
- Charginos/Neutralinos in the light of the Higgs boson
- Summary and conclusion

# Observation of the Higgs boson at the LHC

Observation of the Higgs-like boson at the LHC ushers in a new era in particle physics

ATLAS (hep-ex: 1207.7214) and CMS (hep-ex: 1207.7235)

**CMS Combined local significance**

**Expected:  $5.8\sigma$**

**Observed:  $5.0\sigma$**

**ATLAS Combined local significance**

**(WW, ZZ,  $\gamma\gamma$ )**

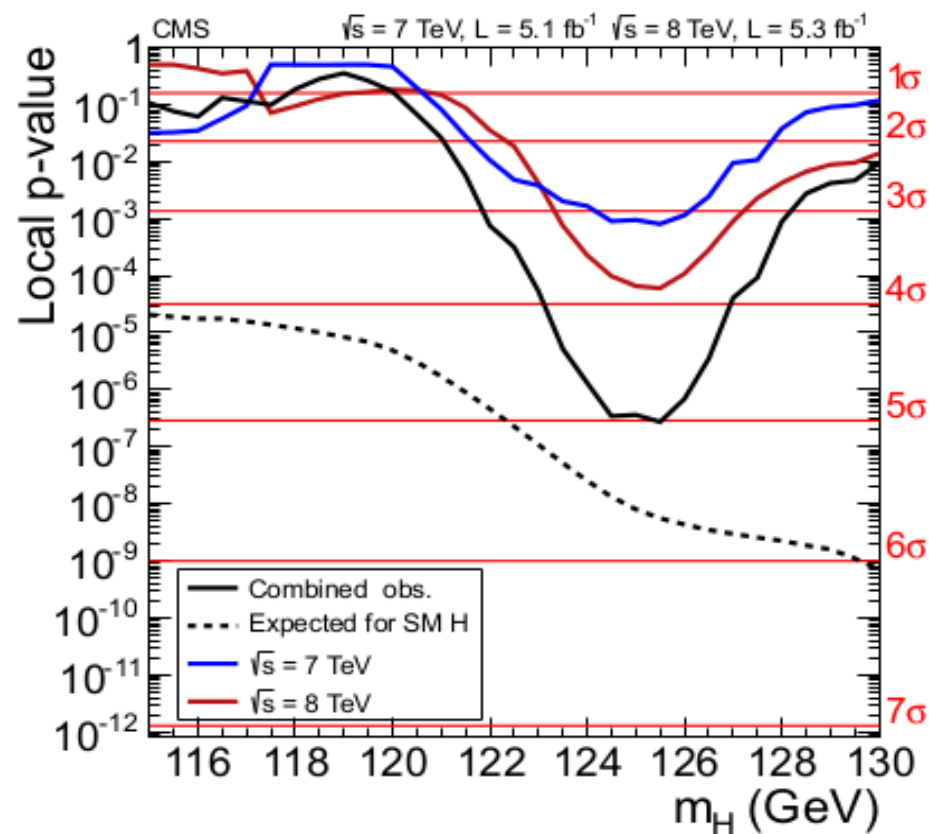
**Expected:  $4.9\sigma$**

**Observed:  $5.9\sigma$**

Combined Mass fit:

$M(\text{CMS}) = 125.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (sys.) GeV}$

$M(\text{ATLAS}) = 126.0 \pm 0.4 \text{ (stat.)} \pm 0.4 \text{ (sys.) GeV}$



## What does $\sim 125$ GeV Higgs indicate?

p-value: probability that background fluctuates to give an excess as large as the (average) signal size expected for a SM Higgs.

# Naturalness in Supersymmetry

arXiv:1203.5539

$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2$$

**“Tuned” due to the Higgs mass - Colored sector**

**SUSY weak sector**

- Individual terms on right side should be comparable in magnitude

- **“Large” cancellations are “unnatural”**

-  $|\mu|$  can be a measure of naturalness

**$\Sigma$  - arises from radiative correction**  $\longrightarrow \Sigma_u \sim \frac{3f_t^2}{16\pi^2} \times m_{\tilde{t}_i}^2 \left( \ln(m_{\tilde{t}_i}^2/Q^2) - 1 \right)$

Stop mass

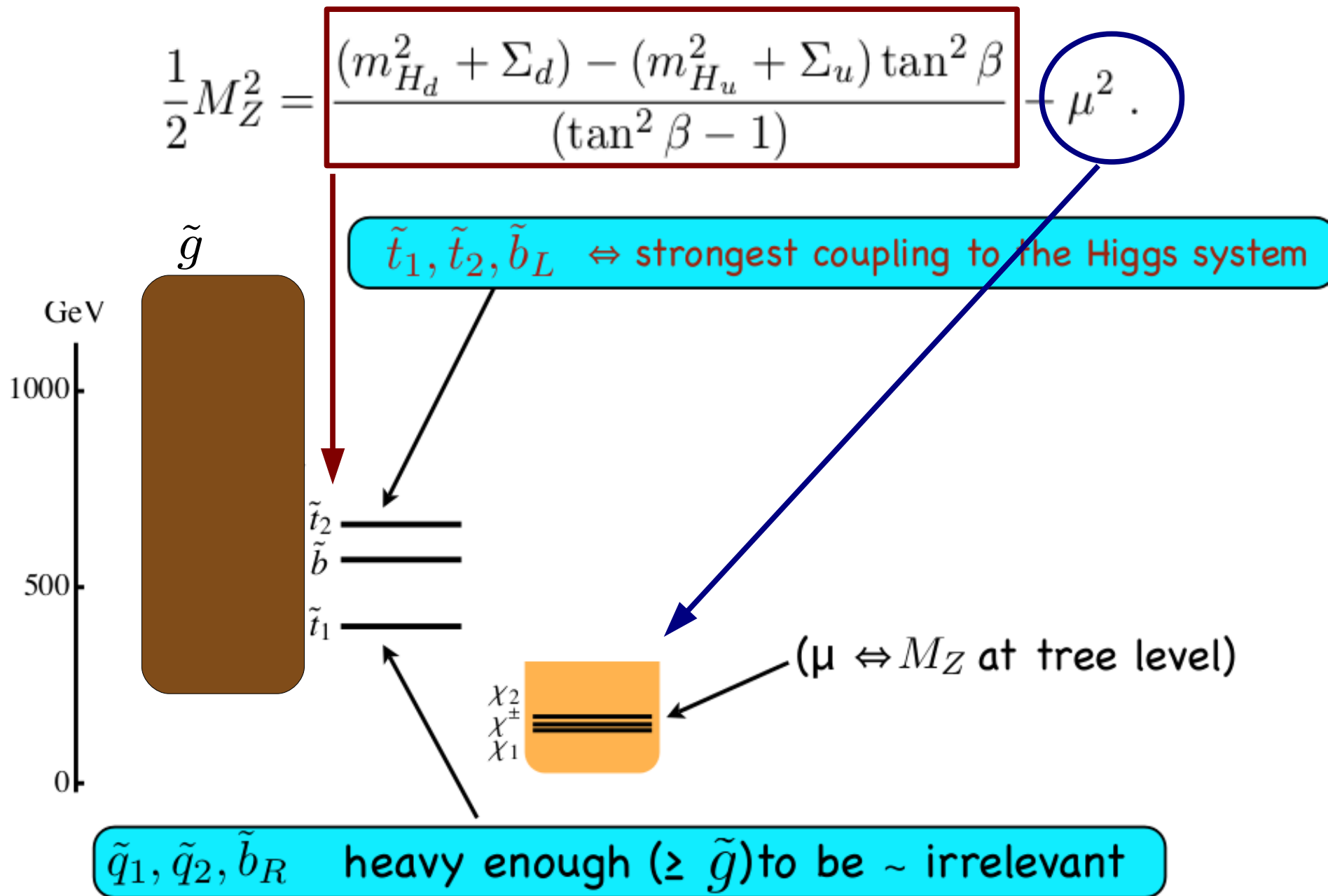
For,  $\Sigma \approx 1/2 M_Z^2 \rightarrow m_{\tilde{t}_i} \approx 500 \text{ GeV}$

Assuming  $\mu \sim 150 \text{ (200) GeV} \rightarrow \text{Mass(stop)} \sim 1 \text{ (1.5) TeV}$

Other heavier Higgs can easily be in the TeV mass range and is perfectly natural:

$$m_A^2 \simeq 2\mu^2 + m_{H_u}^2 + m_{H_d}^2 + \Sigma_u + \Sigma_d$$

# Naturalness in Supersymmetry



# Experimental constraints from LEP

Chargino (  $\tilde{\chi}_i^\pm; i = 1, 2$ ) and Neutralino (  $\tilde{\chi}_i^0; i = 1 - 4$ ) productions at LEP:

$$e^+e^- \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \rightarrow W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow l^+l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Neutralino pairs via s-channel Z or t-channel with slepton exchange

Using mSUGRA or CMSSM framework

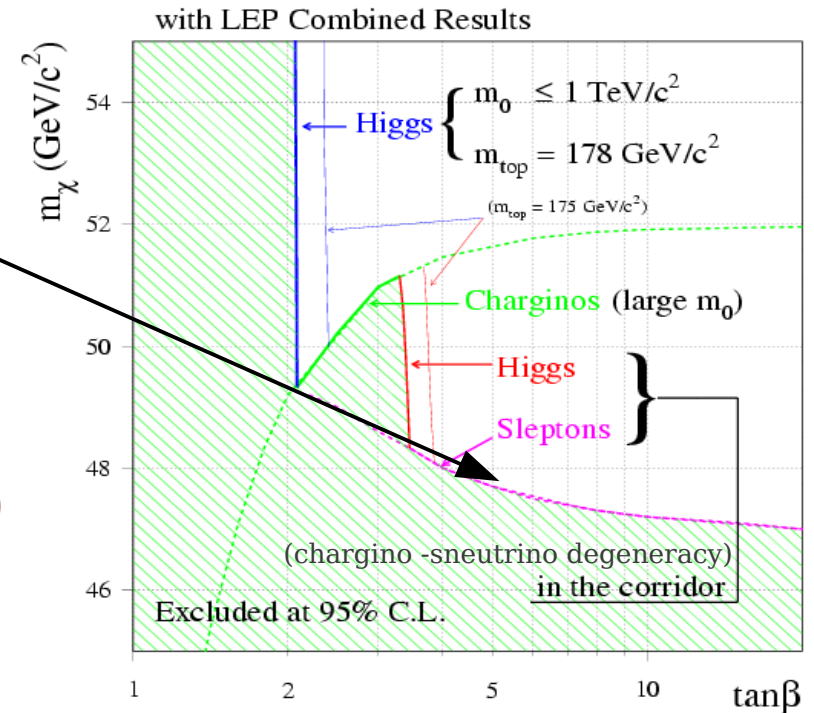
(assuming mixing in stau sector is small)

**LSP mass below 47/50 GeV is excluded**

However several assumptions are involved:

- mSUGRA / CMSSM
- gaugino mass unification
- $\tan\beta < 3.3$  limits at large  $M_0$  (+higgs, chargino)
- ( $M_0$  - common sfermion mass at GUT)
- $\tan\beta > 3.3$  the limit is using small  $M_0$

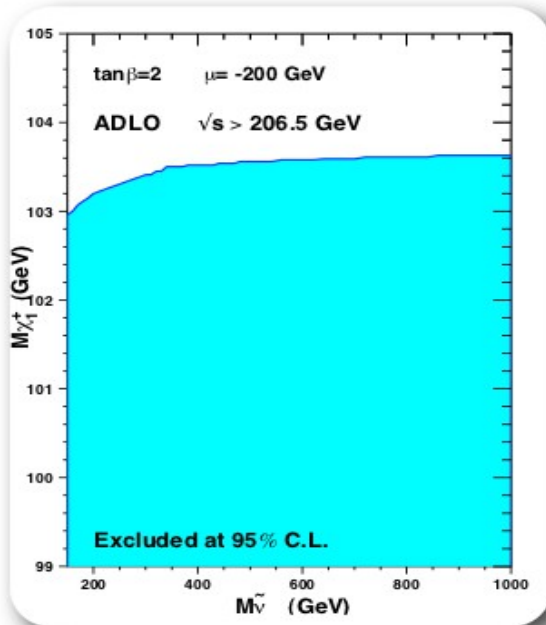
**No mass limit in general outside these assumptions**



# Experimental constraints from LEP

Charginos via: s-channel  $\gamma/Z$  or t-channel with sneutrino exchange

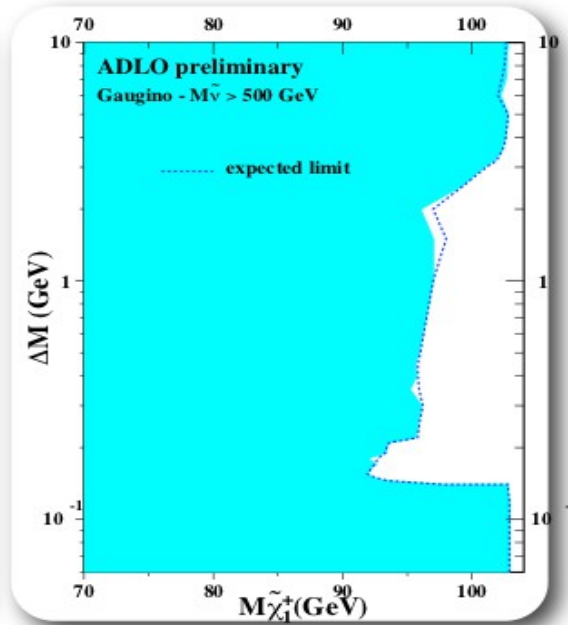
**canonical case**



**$m_{\tilde{\chi}_1^\pm} > 103.5$  GeV  
for  $m_{\text{sneutrino}} > 300$  GeV**

LEPSUSYWG/01-03.1

**degenerate case**



**$m_{\tilde{\chi}_1^\pm} > 91.9 / 92.4$   
GeV**

LEPSUSYWG/02-04.1

Unification of gaugino masses  
at GUT scale is assumed.

$$\begin{aligned} - M_1 &= (5/3) \tan^2(\theta_W) M_2 \\ &\sim 0.5 M_2 \end{aligned}$$

Canonical case:

- With  $M(\text{sneutrino}) > 300$  GeV

Degenerate case:

-  $M_1$  and  $M_2$  nearly degenerate

- Large  $M_0$  ( $m(\text{snu}) \sim 500$  GeV)

In general Charginos up to  $\sim 100$  GeV in mass are excluded by the LEP experiments

# Experimental constraints from LEP

Chargino ( $\tilde{\chi}_i^\pm; i = 1, 2$ ) and Neutralino ( $\tilde{\chi}_i^0; i = 1 - 4$ ) productions at LEP:

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$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Neutralino pairs via s-channel Z or t-channel with slepton exchange

Using mSUGRA or CMSSM framework

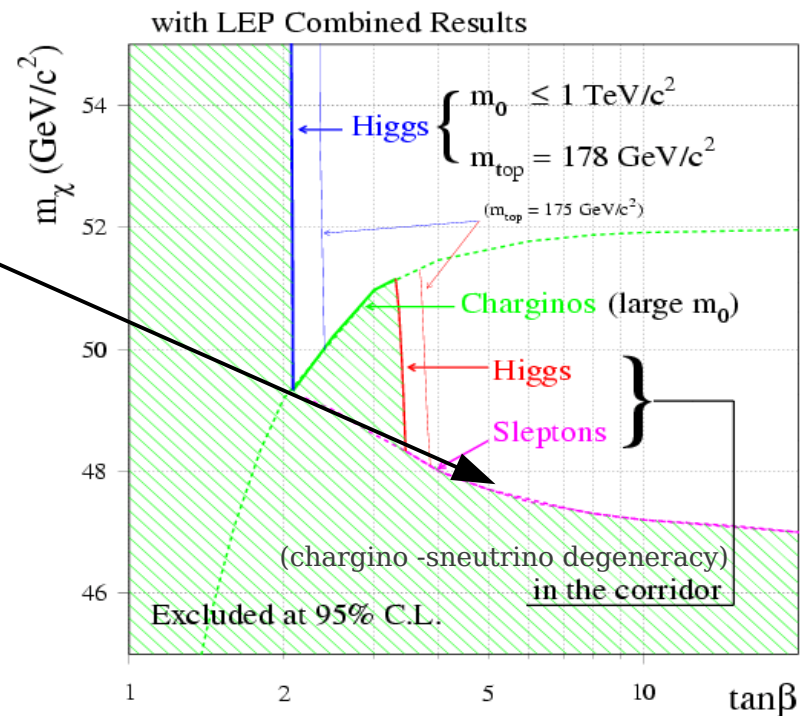
(assuming mixing in stau sector is small)

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**No mass limit in general outside these assumptions**



# Experimental constraints from Tevatron

D0 Collaboration:  $p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$

Three leptons + MET signature

- e,  $\mu$ , and  $\tau$

4 Channels (e $\mu$ l,  $\mu\mu$ l, e $\mu$  $\tau$ l,  $\mu\tau$ l)

Dominant bkg: WZ, ZZ in MET tails

Within the context of MSUGRA

Assuming:

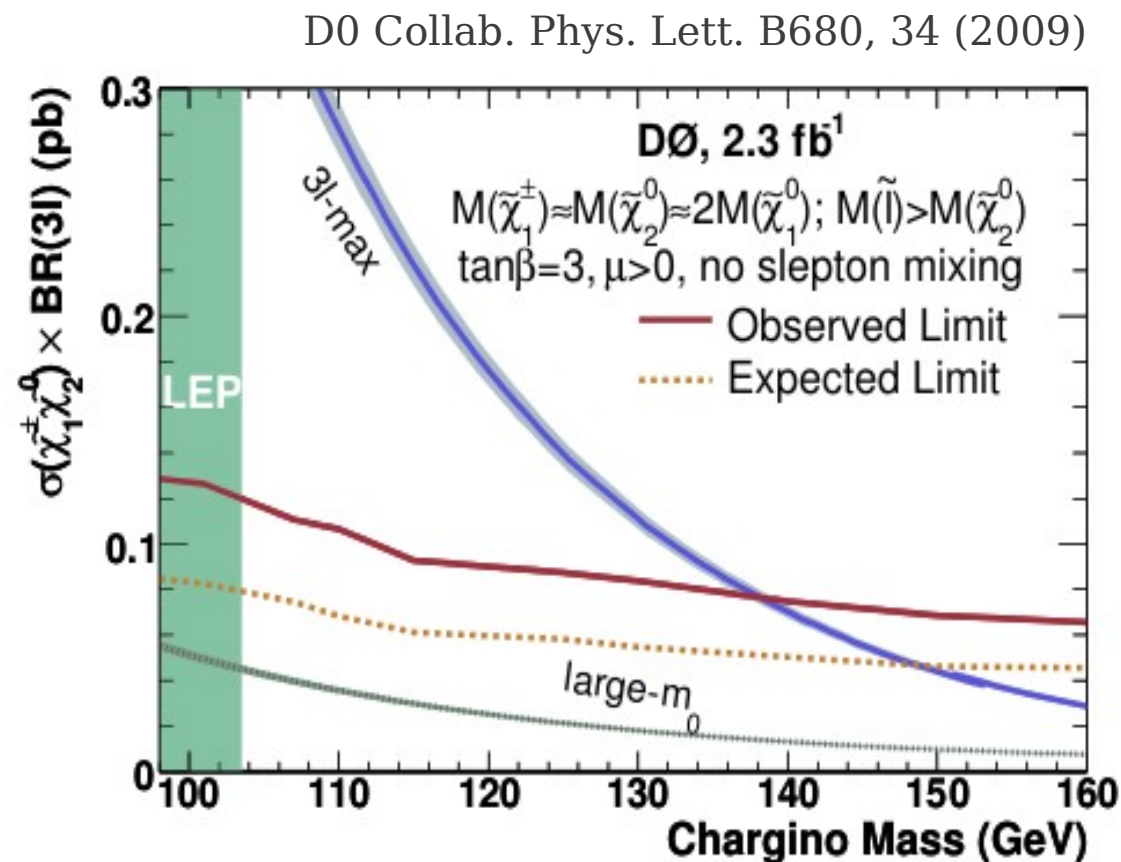
$$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \sim 2m_{\tilde{\chi}_1^0}$$

- and neglecting the slepton mixing
- sleptons and sneutrinos heavier than lightest charginos and next lightest neutralino

In the limit of heavy sleptons (large  $m_0$  scenario):

- the slepton mass is just above mass of  $\tilde{\chi}_2^0$ , leptonic BR is maximized (3l max case)

Chargino mass < 138 GeV is excluded by this study



# Experimental constraints from Tevatron

CDF Collaboration:  $p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$

CDF Note: 10636

CDF Run II Preliminary (L=5.8 fb<sup>-1</sup>)

Three leptons + MET signature

Several SRs in the plane - MET & M<sub>ll</sub>

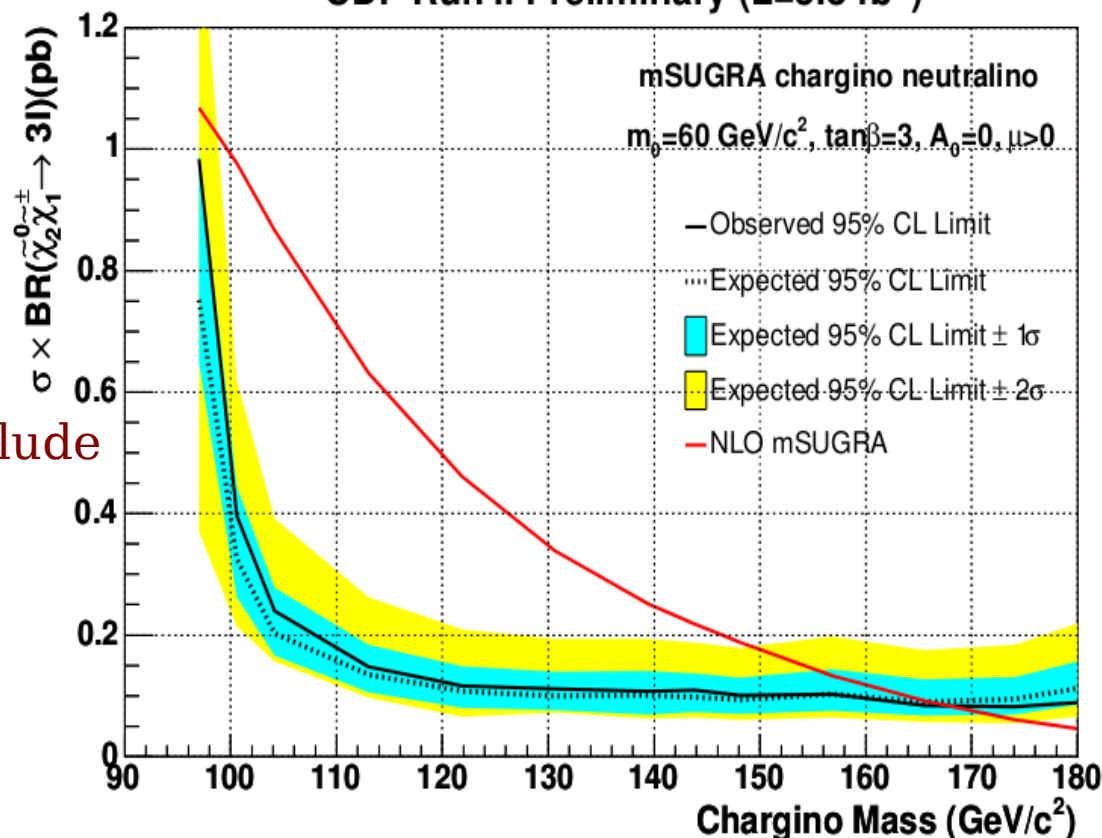
Modes:

- eel,  $\mu\mu l$  ; l = e,  $\mu$ ,  $\tau$  (or single track)
- Expanded the acceptance & also include low p<sub>T</sub> leptons ~ 5 GeV threshold.

Major backgrounds:

- WZ, ZZ, dileptons + fakes

Within the context of MSUGRA

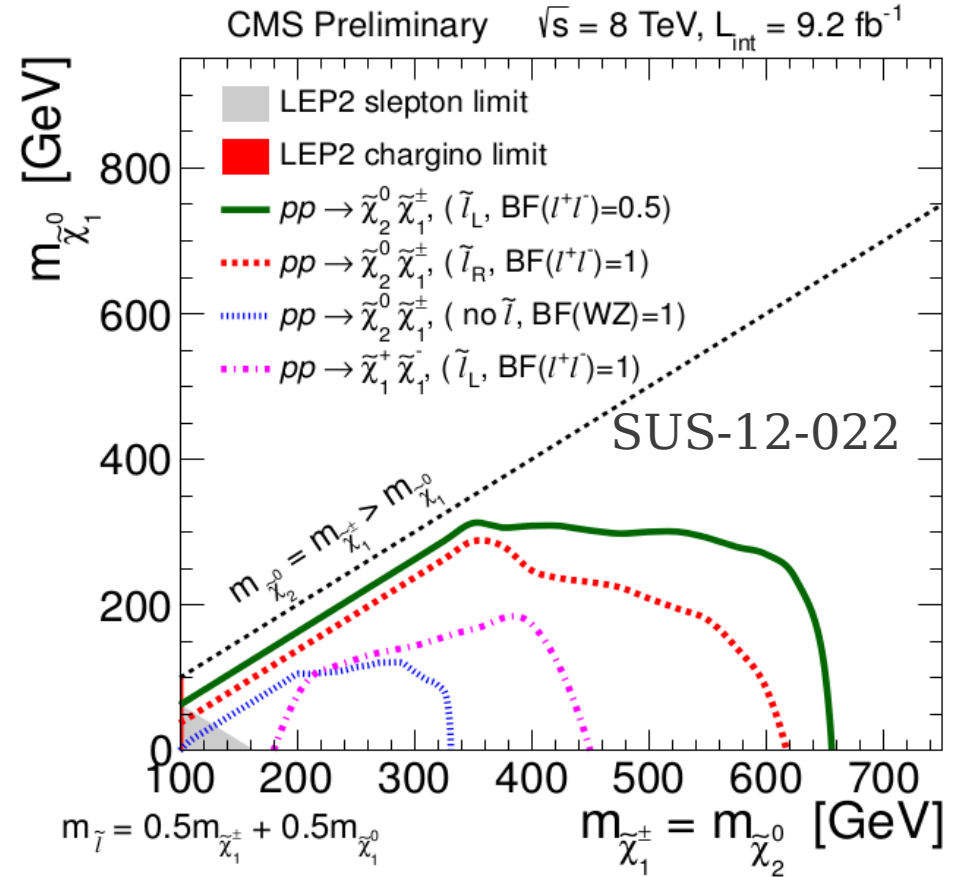
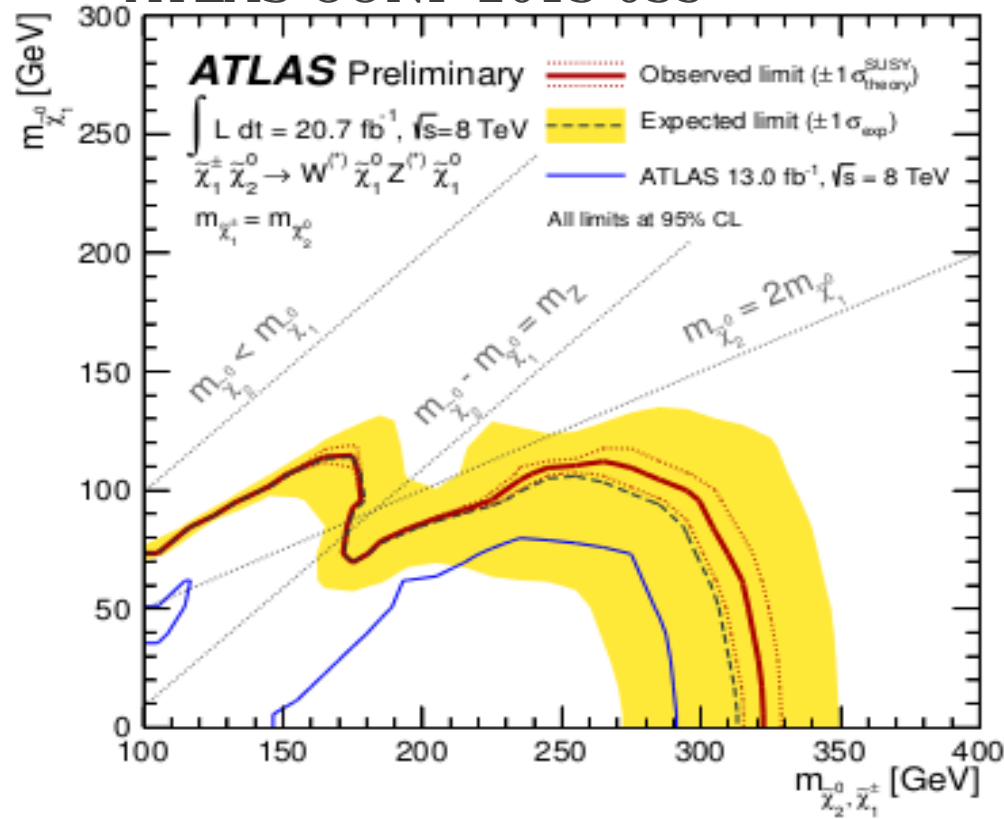


Exclude at 95% CL  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \times BR(l\bar{l}l)$  above 0.1 fb

Chargino mass below 168 GeV is excluded by this study

# Direct electroweak production at the LHC

ATLAS-CONF-2013-035



Limits are weaker :

100% BR – Usually not realized

# Natural SUSY Charginos/Neutralinos

## Assuming Higgs connection

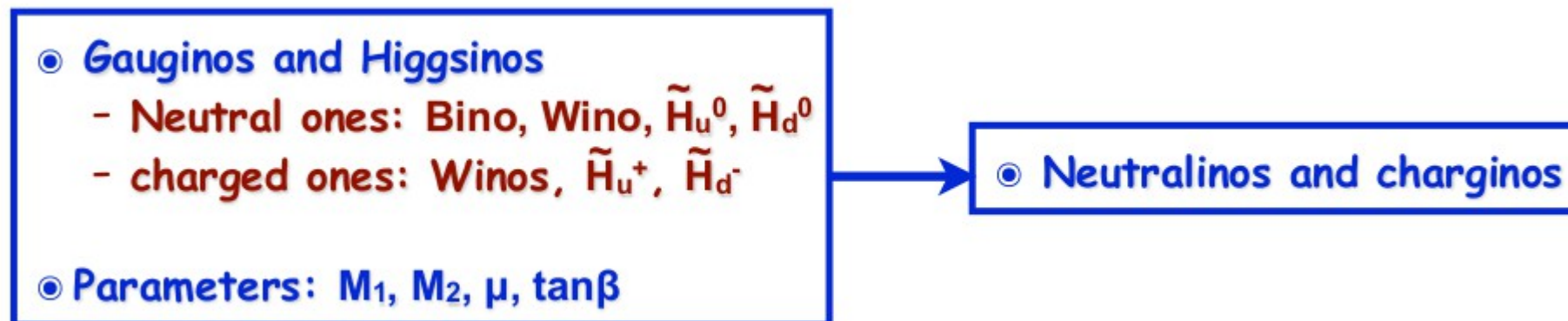
- Natural SUSY  $\rightarrow$  Light gauginos and Higgsinos

## Colored superparticles might be heavy (See previous slides)

- Electroweak sector + stops/sbottoms might be the only accessible particles
- no indication from current LHC searches,  $m_{sq'}, m_{\text{gluino}} > 1 \text{ TeV}$

## Connection to lepton collider

In MSSM :



# Natural SUSY Charginos/Neutralinos

$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2.$$

Assume LSP based on SUSY breaking mass parameters  $M_1$ ,  $M_2$  and  $\mu$

- Decouple the SUSY colored sector

There can be three cases:

a) Bino LSP ( $M_1 < M_2, \mu$ )

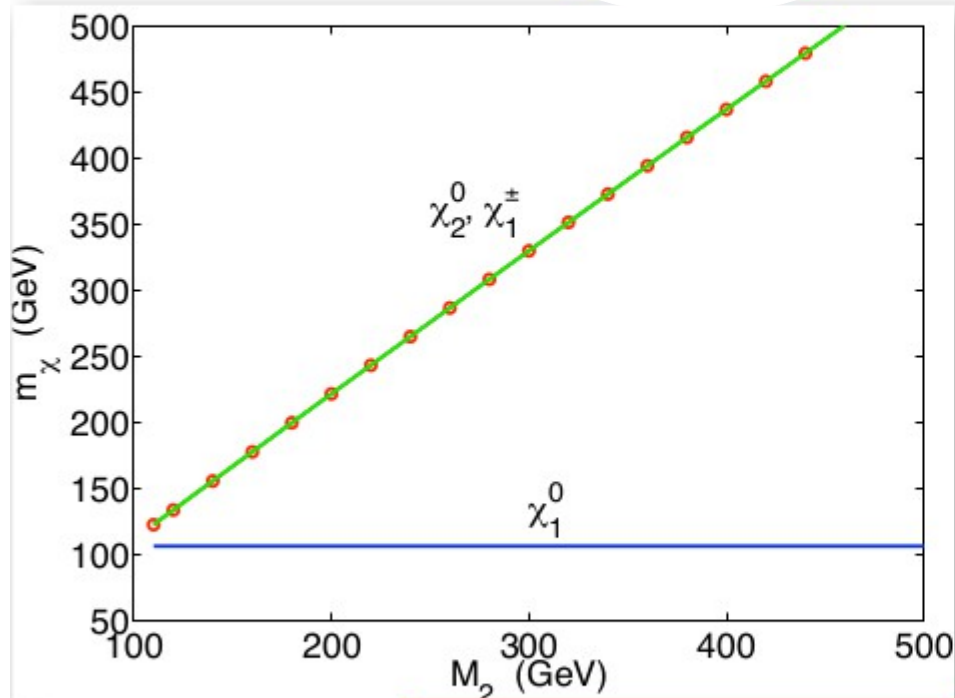
b) Wino LSP ( $M_2 < M_1, \mu$ )

c) Higgsino LSP ( $\mu < M_1, M_2$ )

# Masses: Bino LSP

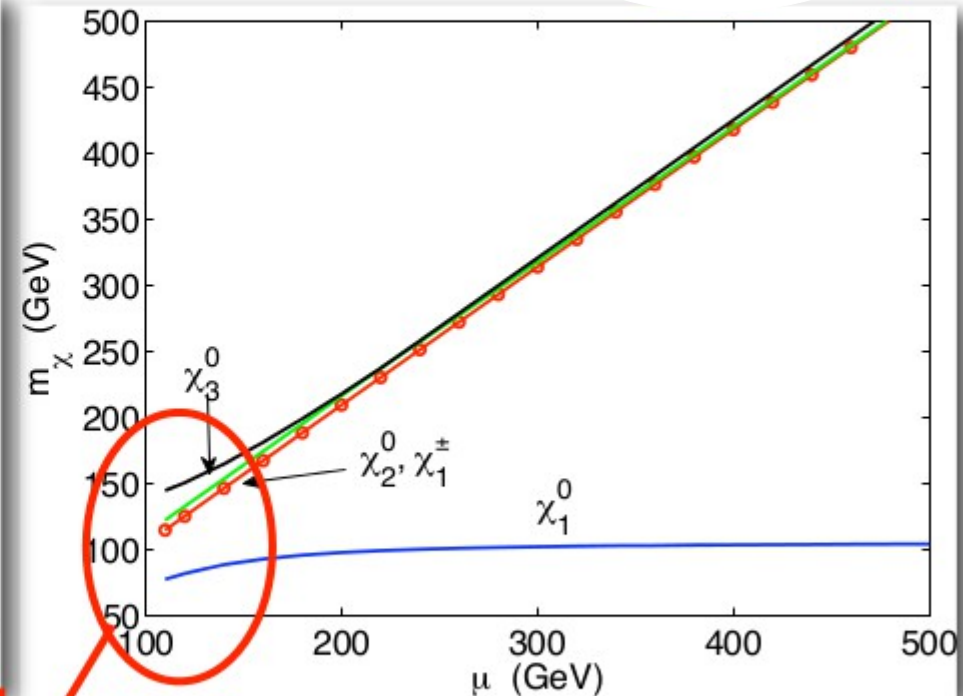
**Case AI:**  
 $M_1 < M_2 < \mu$

$\mu = 1 \text{ TeV}$



**Case All:**  
 $M_1 < \mu < M_2$

$M_2 = 1 \text{ TeV}$



**large mixing, natural  
compressed spectrum**

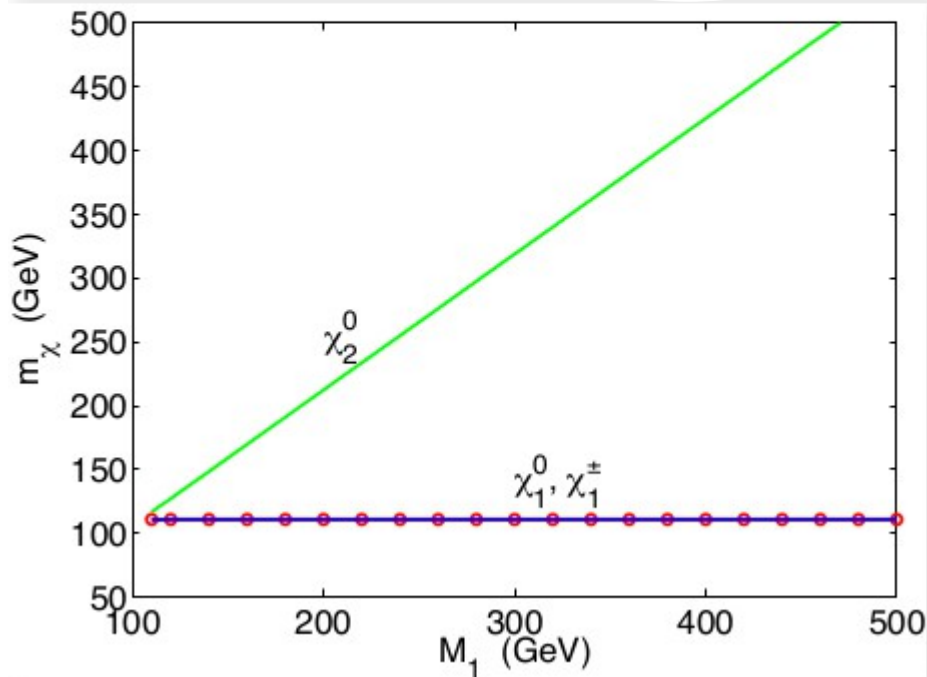
Case AI :  $M_2 < \mu$ ,  $\chi_1^{\pm}, \chi_2^0$  are Wino – like;  $\chi_2^{\pm}, \chi_{3,4}^0$  are Higgsino – like;

Case AII :  $\mu < M_2$ ,  $\chi_1^{\pm}, \chi_{2,3}^0$  are Higgsino – like,  $\chi_2^{\pm}, \chi_4^0$  are Wino – like.

# Masses: Wino LSP

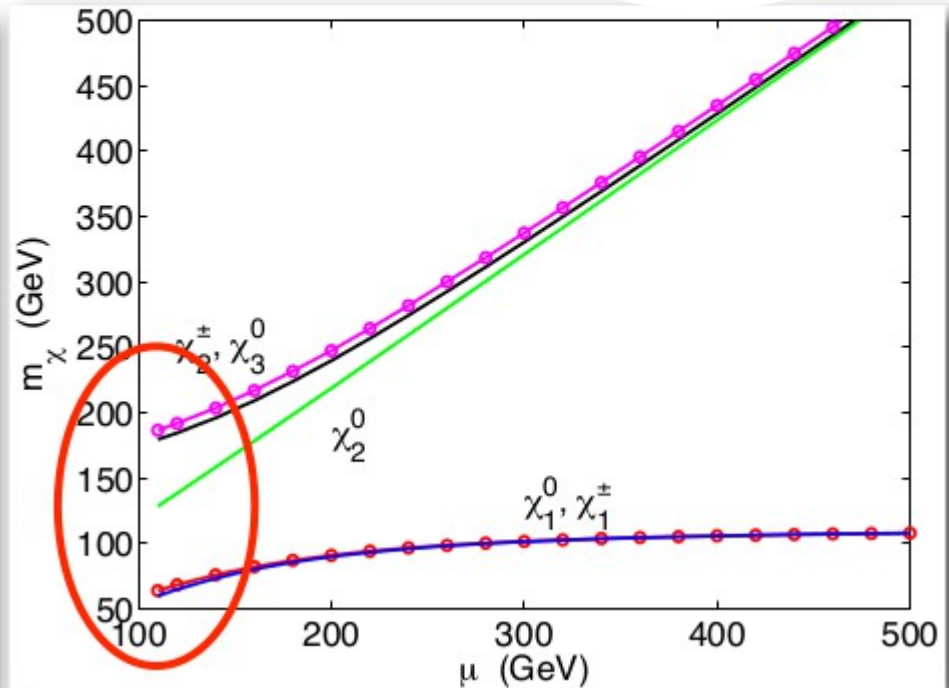
**Case BI:**  
 $M_2 < M_1 < \mu$

$\mu = 1 \text{ TeV}$



**Case BII:**  
 $M_2 < \mu < M_1$

$M_1 = 1 \text{ TeV}$



With wino LSP:

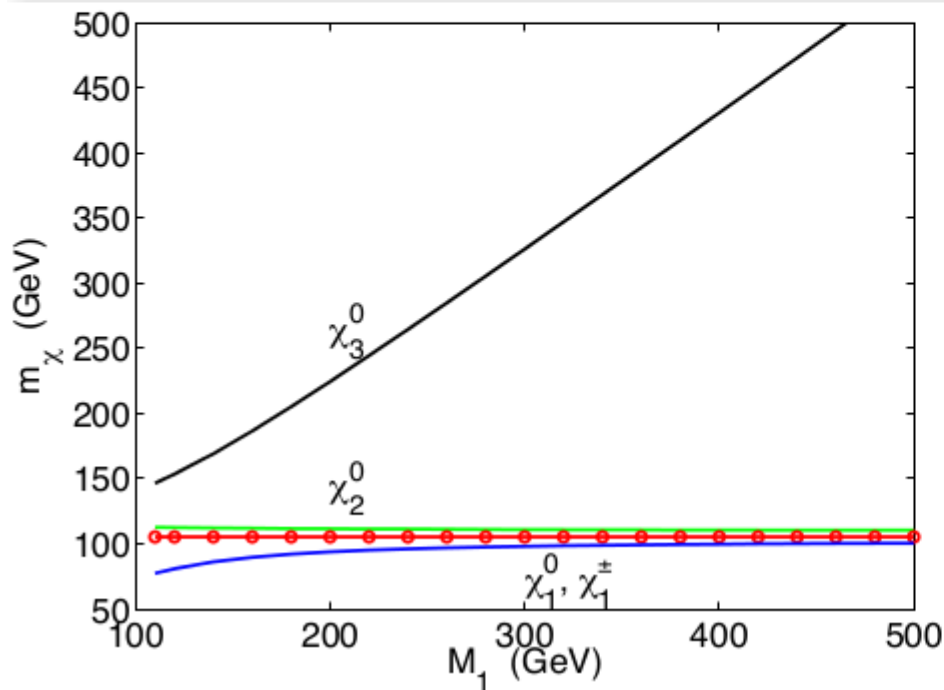
Case BI :  $M_1 < \mu$ ,  $\chi_2^0$  Bino – like;  $\chi_2^\pm, \chi_{3,4}^0$  Higgsino – like;

Case BII :  $\mu < M_1$ ,  $\chi_{2,3}^\pm, \chi_{2,3}^0$  Higgsino – like;  $\chi_4^0$  Bino – like.

# Masses: Higgsino LSP

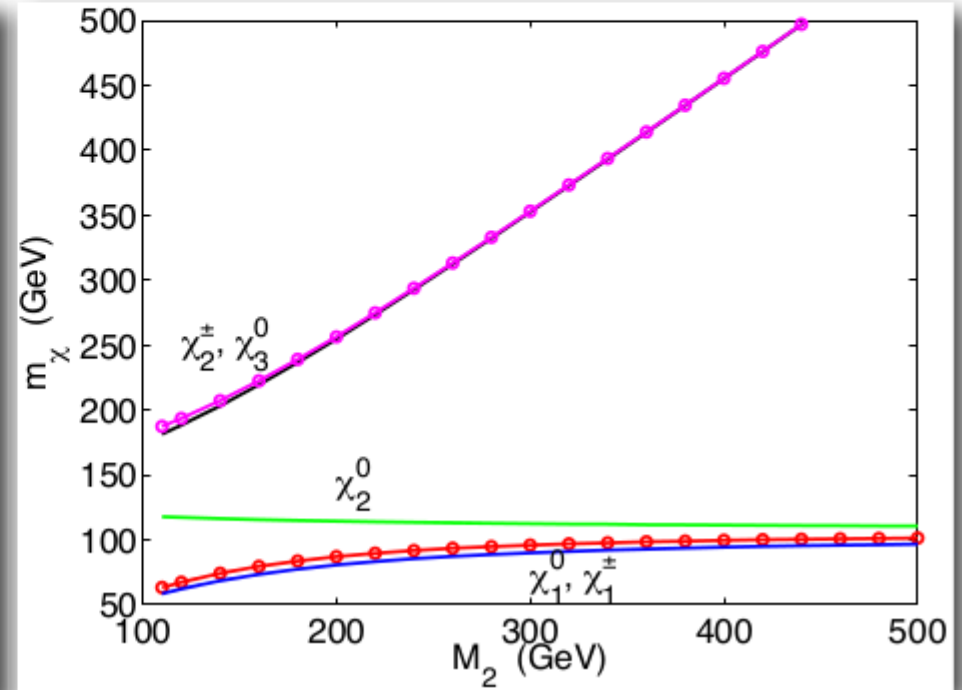
**Case CI:**  
 $\mu < M_1 < M_2$

$M_2 = 1 \text{ TeV}$



**Case CII:**  
 $\mu < M_2 < M_1$

$M_1 = 1 \text{ TeV}$

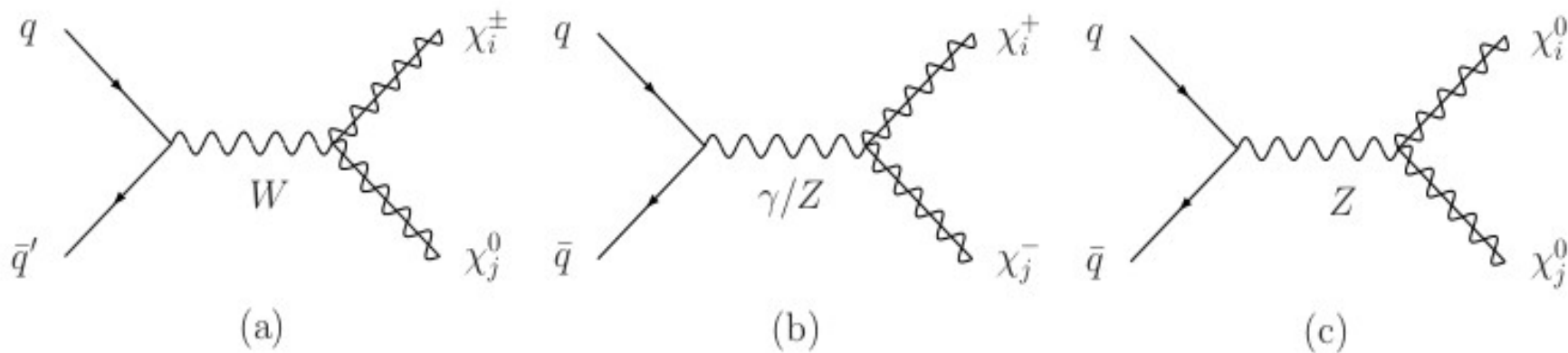


With higgsino LSP:

Case CI :  $M_1 < M_2$ ,  $\chi_3^0$  Bino – like;  $\chi_2^\pm, \chi_4^0$  Wino – like;

Case CII :  $M_2 < M_1$ ,  $\chi_2^\pm, \chi_3^0$  Wino – like;  $\chi_4^0$  Bino – like.

# Productions of SUSY weak sector

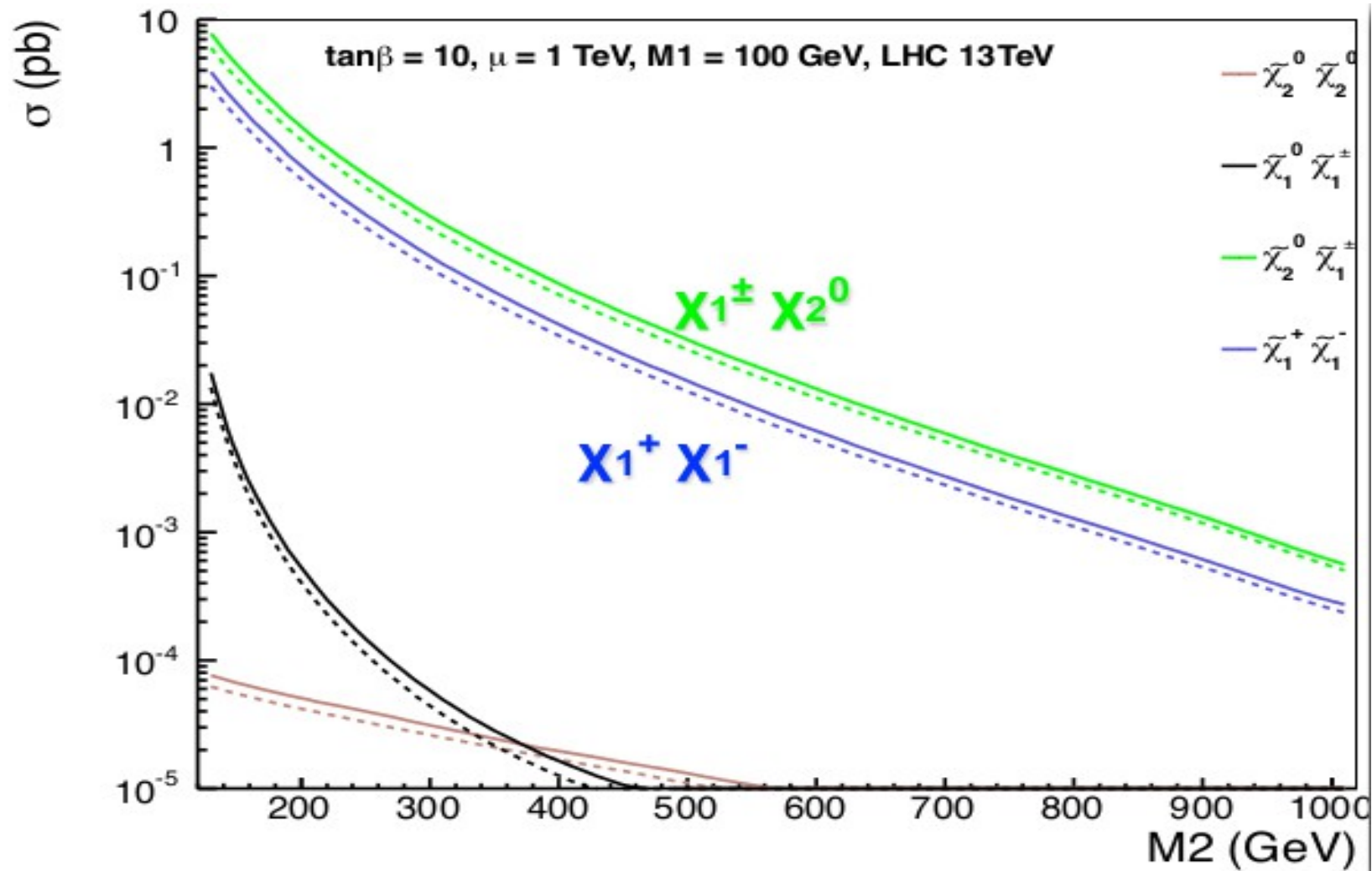


## Dominant production:

- Wino pair production:  $\chi_i^+ \chi_j^-, \chi_i^\pm \chi_j^0$
- Higgsino pair production:  $\chi_i^+ \chi_j^-, \chi_i^\pm \chi_j^0, \chi_i^0 \chi_j^0$

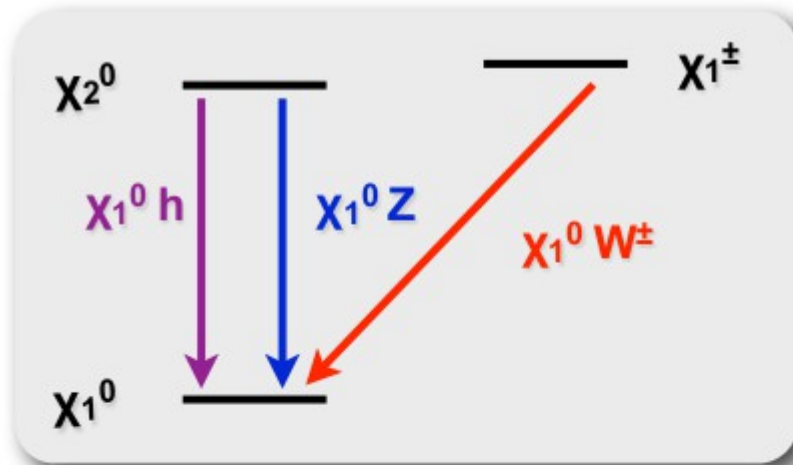
# Productions of Bino LSP, Wino NLSP

Case A1:  $M_1 < M_2 < \mu$



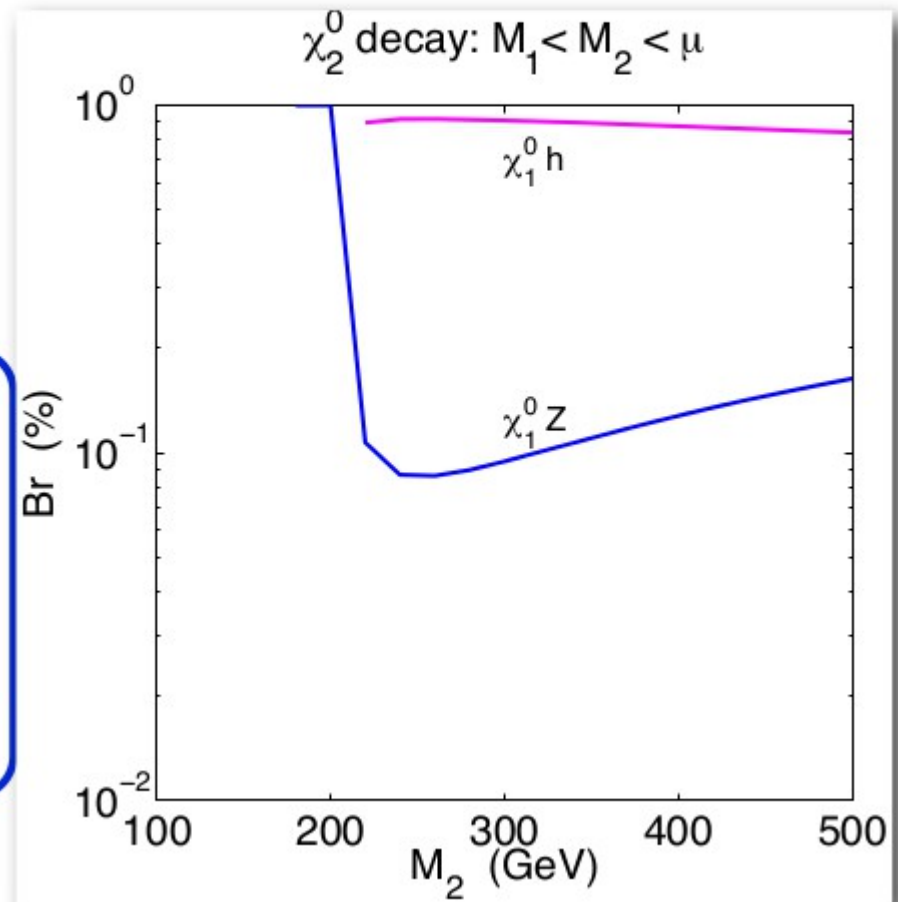
Dominant contributions are from:  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 X, \tilde{\chi}_1^+ \tilde{\chi}_1^- X$

# Decays with Bino LSP, Wino NLSP



$\chi_1^\pm$  decay 100% via on/off-shell  $W$

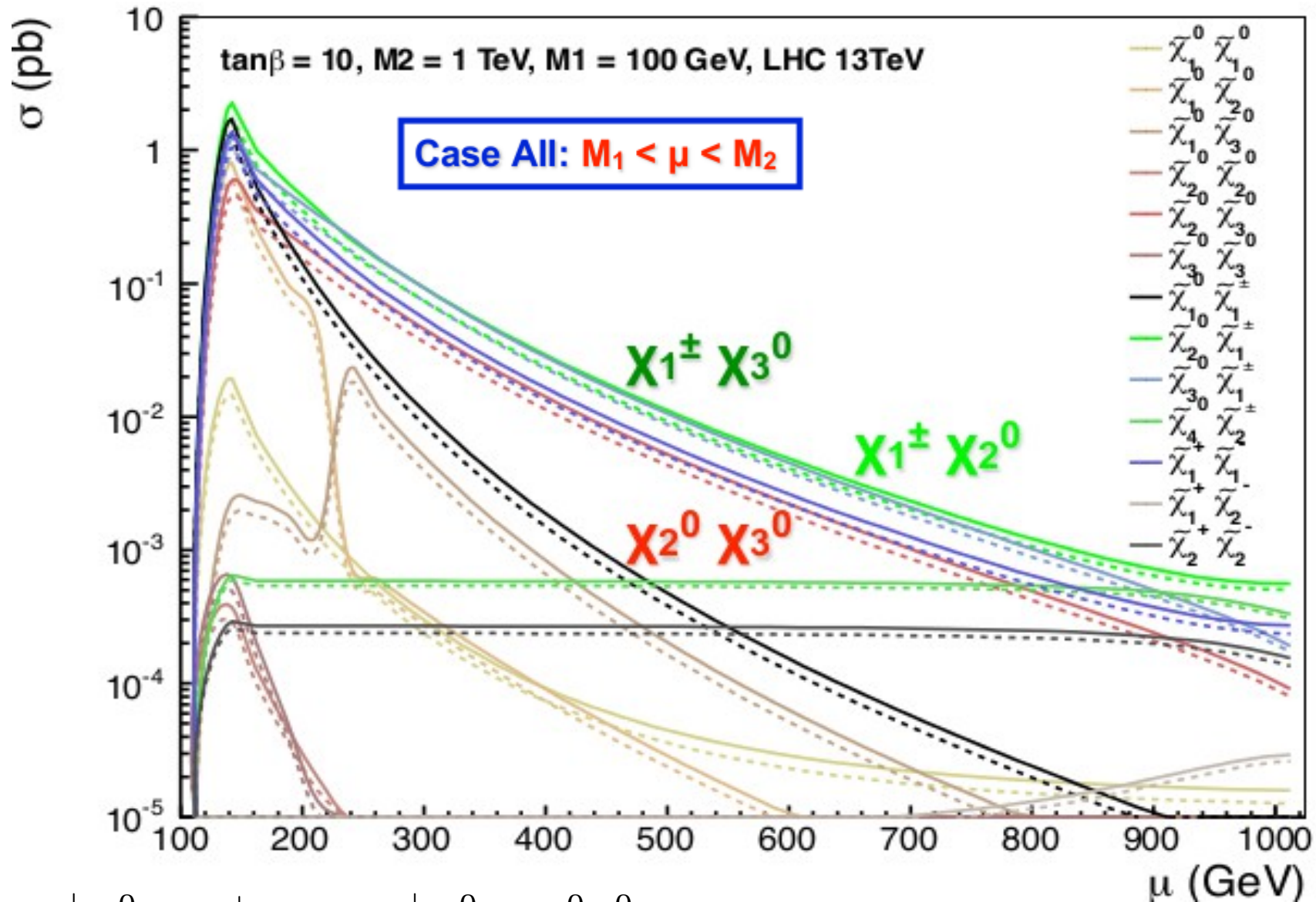
- below  $h$  threshold, decay via on/off-shell  $Z$
- $\chi_2^0$  on-shell decay to  $h$  dominate over on-shell  $Z$  for  $\mu > 0$
- $\chi_2^0$  decay to  $h$  and  $Z$  flipped for  $\mu < 0$



Dominant contributions are from:

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 X, \tilde{\chi}_1^+ \tilde{\chi}_1^- X; \chi_1^\pm \rightarrow W^\pm \chi_1^0, \chi_2^0 \rightarrow (h/Z) \chi_1^0$$

# Productions of Bino LSP, Higgsino NLSP



$$pp \rightarrow \chi_1^\pm \chi_2^0 X, \chi_1^+ \chi_1^- X, \chi_1^\pm \chi_3^0 X, \chi_2^0 \chi_3^0 X$$

$$\chi_1^\pm \rightarrow W^\pm \chi_1^0; \chi_2^0 \rightarrow (h/Z) \chi_1^0, \chi_3^0 \rightarrow (Z/h) \chi_1^0$$

For details on other LSP ( $M_2, \mu$ )  
→ See the upcoming paper

# SUSY weak productions

Final states that can be explored:

$$WW, WZ, Wh, Zh, ZZ, hh$$

- BR(WZ) < 100% in most cases, sometimes highly suppressed
- Wh complementary to WZ channel : a new discovery mode
- Zh/hh should also be explored.

Experimentally challenging depending on “compression” between the mass states:  
(e.g: Also the depends on the choice of the LSP)

- If the mass difference is in MeV:  $\chi_2^0 - \chi_1^0$  or  $\chi_1^\pm - \chi_1^0$ 
  - Expect “appearing tracks” within few cms if the associated particle is neutral
  - Expect highly ionizing tracks (dE/dx) associated with charged particle
- If the mass difference is in GeV  $\rightarrow$  prompt decays

# SUSY weak productions

## In terms of searches:

### 1. If both parents are un-compressed:

- Standard analysis, trigger on any or both of the visible decay products

### 2. If one of the parents is compressed e.g: $\chi_2^0 \chi_1^\pm$ ; $M(\chi_1^\pm) \approx M(\chi_1^0)$

- Use trigger based on one visible decay product

### 3. If both parents are compressed

- e.g:  $\chi_1^+ (\rightarrow W \chi_1^0) \chi_1^- (\rightarrow W \chi_1^0)$ ;  $M(\chi_1^\pm) \approx M(\chi_1^0)$

- Use mono-jet kind of analysis with trigger on ISR jets (Parked data?)

# Possible future LHC searches with Higgs in the final state

## ● Wh channel: 1l+jets + MET

- Isolated  $e(\mu)$ ,  $P_t > 30(20)$  GeV,  $|\eta| < 2.5$
- Veto any additional  $e/\mu$  with  $P_t > 10$  GeV,  $|\eta| < 2.5$
- Veto any Taus or isolated Tracks
- 2 Jets  $P_t > 30$  GeV,  $|\eta| < 2.5$
- Veto 3rd Jet with  $P_t > 20$  GeV
- 2 bjets with  $P_t > 30$  GeV,  $|\eta| < 2.5$
- 2 bjets in one hemi-sphere ←
- Invariant mass of two bjets  $100 < M_{bb}$  (GeV)  $< 140$
- $M_T$  (MET and the Higgs)  $> 200$  GeV
- $MET > 50$  GeV

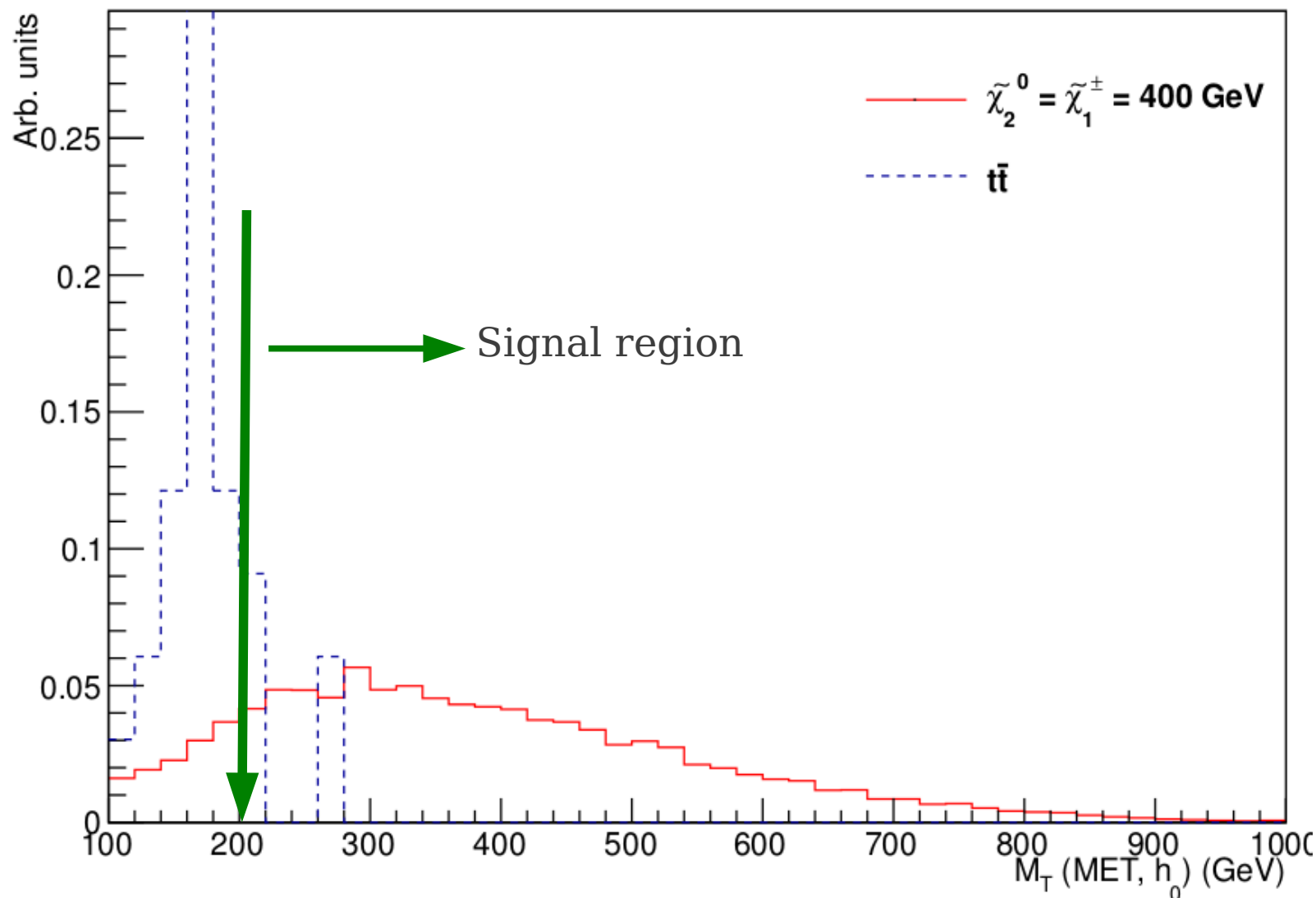
**Signal regions:**

**$(M_T, MET) > (200, 50), (600, 50), (200, 100), (600, 100)$  GeV**

10 fb<sup>-1</sup>

Processes	MET > 50, $M_T > 200$ (Baseline)	MET > 50, $200 < M_T < 400$	MET > 50, $400 < M_T < 600$	MET > 50, $M_T > 600$	MET > 100, $M_T > 200$	MET > 100, $200 < M_T < 400$	MET > 100, $400 < M_T < 600$	MET > 100, $M_T > 600$
Total bg	$46.15 \pm 12.01$	$43.27 \pm 11.96$	$2.40 \pm 1.02$	$0.48 \pm 0.48$	$33.63 \pm 10.69$	$30.75 \pm 10.63$	$2.40 \pm 1.02$	$0.49 \pm 0.48$

# Possible LHC searches with Higgs in the final state

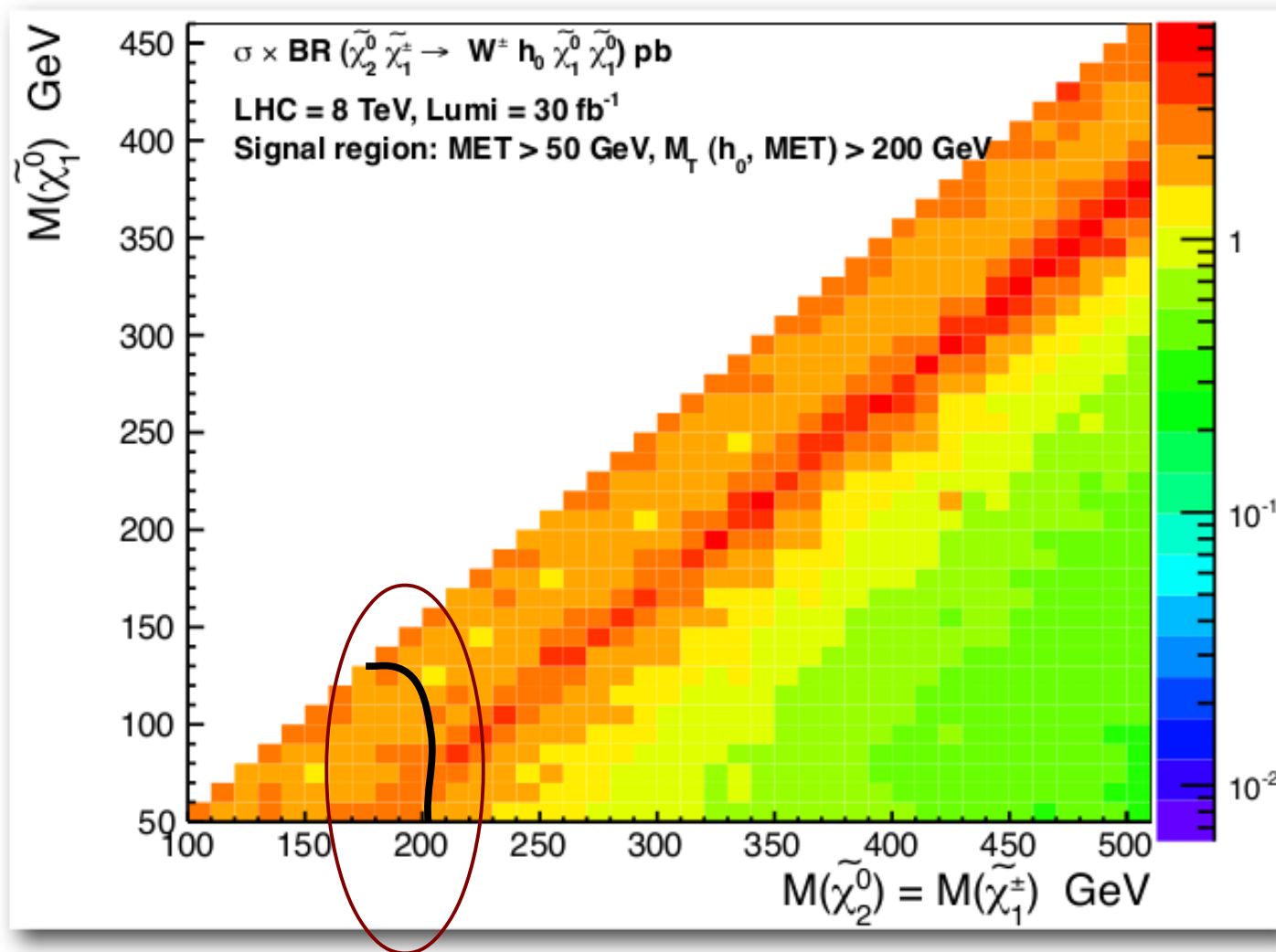


- Higgs Transverse Mass (Event simulation using Delphes)
- Background dominated by  $t\bar{t}$  events

# Possible LHC searches with Higgs in the final state

**Wh: 1l+jets + MET**

**95% C.L. upper limit on signal cross section**



With background only hypothesis, one can be sensitive to  $\sim 200 \text{ GeV}$  in mass

# Summary and Conclusion

Naturalness in SUSY can be valuable guiding principle for current/future searches

SUSY results from ATLAS and CMS show the breath of physics analyses

SUSY electroweak searches from the LHC

- the constraints on direct electroweak productions are soft.

Discovery of Higgs is just a starting point to move into a new territory

Search for new physics with Higgs in the final state

Studies towards naturally compressed spectra

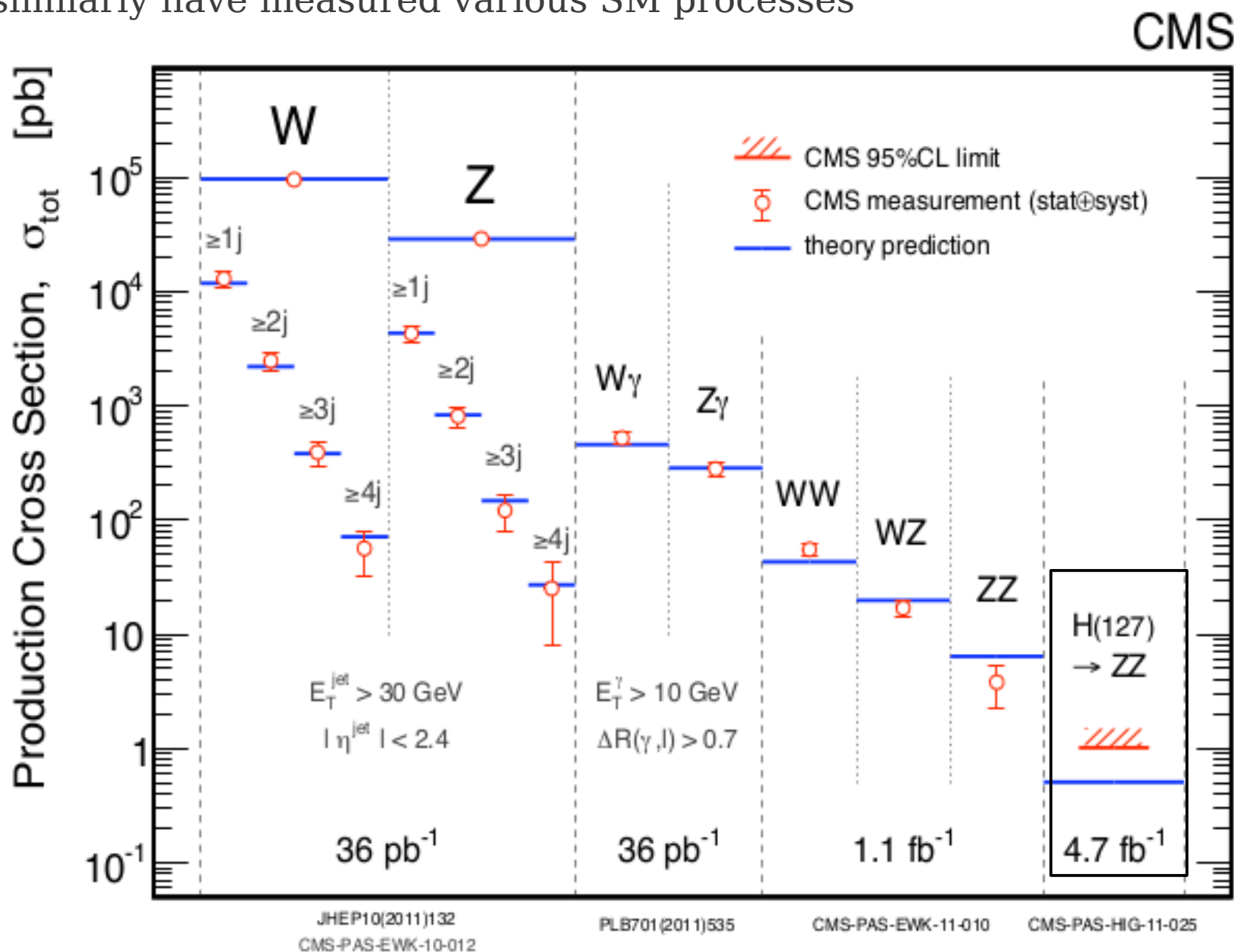
→ Essential for next phase of LHC studies

Backup slides

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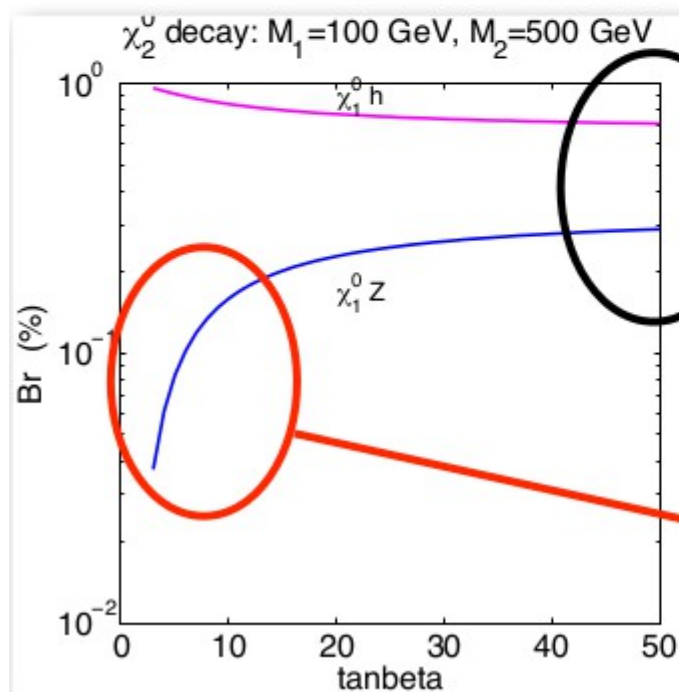
# Standard Model Measurements

ATLAS similarly have measured various SM processes



# tanbeta dependency

- decay occur via mixing through Higgsino
- $M_2 \gg M_1$ ,  $\chi_2^0 \rightarrow \chi_1^0 Z$  dominated by the decay via  $Z_L$  (goldstone mode  $G^0$ )
- $h, G^0$  as mixture of  $H_u^0$  and  $H_d^0$



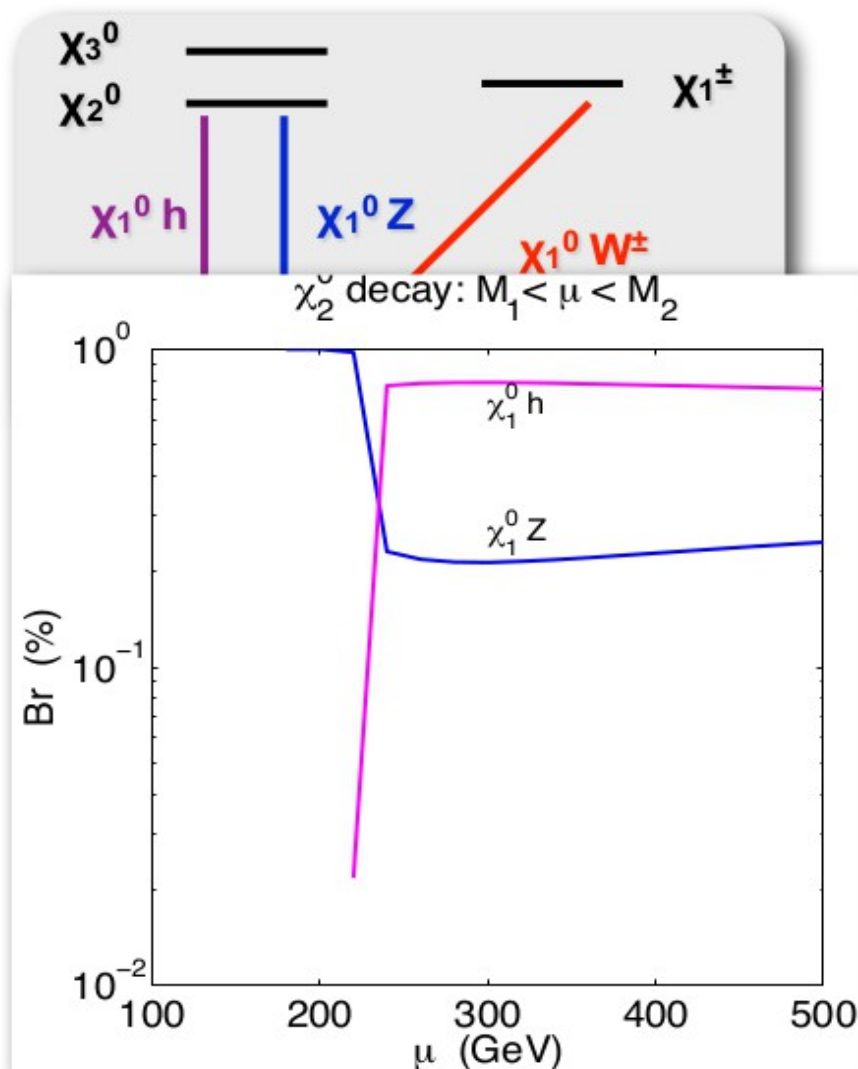
$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 h) \propto \left( 2s_{2\beta} + \frac{M_2}{\mu} \right)^2 \left[ (M_2 + M_1)^2 - m_h^2 \right],$$

$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 Z) \propto \left( c_{2\beta} \frac{M_2}{\mu} \right)^2 \left[ (M_2 - M_1)^2 - m_Z^2 \right].$$

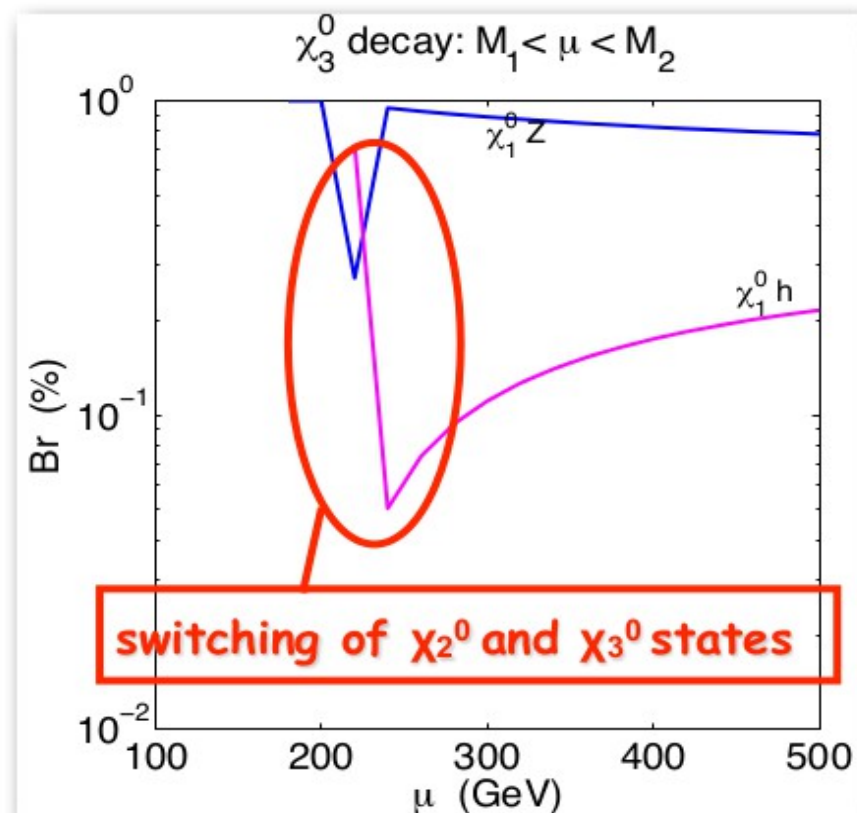
large  $\tan\beta$ ,  $[(M_2 + M_1)^2 - m_h^2] / [(M_2 - M_1)^2 - m_h^2]$

small  $\tan\beta$ , Z channel relatively suppressed

## Case AII: Bino LSP-Higgsino NLSP



$\chi_1^\pm$  decay 100% via on/off-shell W



# Neutralinos

## ● Neutralinos

$$\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$$

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

**M<sub>1</sub>** Bino

**M<sub>2</sub>** Wino

**|μ|** Higgsino

**|μ|** Higgsino

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}\left(\frac{m_Z}{M} \frac{m_Z}{M'}\right) & \mathcal{O}\left(\frac{m_Z}{M}\right) & \mathcal{O}\left(\frac{m_Z}{M}\right) \\ \mathcal{O}\left(\frac{m_Z}{M} \frac{m_Z}{M'}\right) & 1 & \mathcal{O}\left(\frac{m_Z}{M}\right) & \mathcal{O}\left(\frac{m_Z}{M}\right) \\ \mathcal{O}\left(\frac{m_Z}{M}\right) & \mathcal{O}\left(\frac{m_Z}{M}\right) & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \mathcal{O}\left(\frac{m_Z}{M}\right) & \mathcal{O}\left(\frac{m_Z}{M}\right) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

# Charginos

- Charginos

$$\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$$

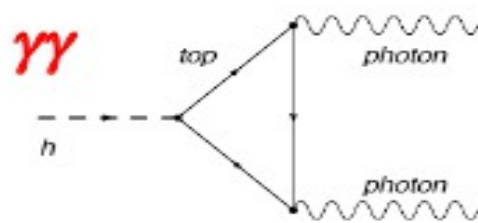
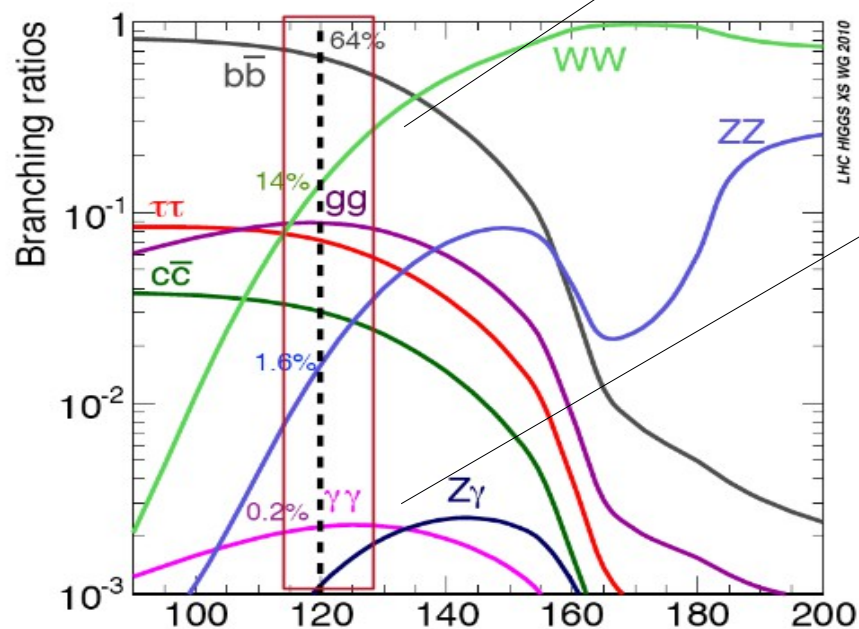
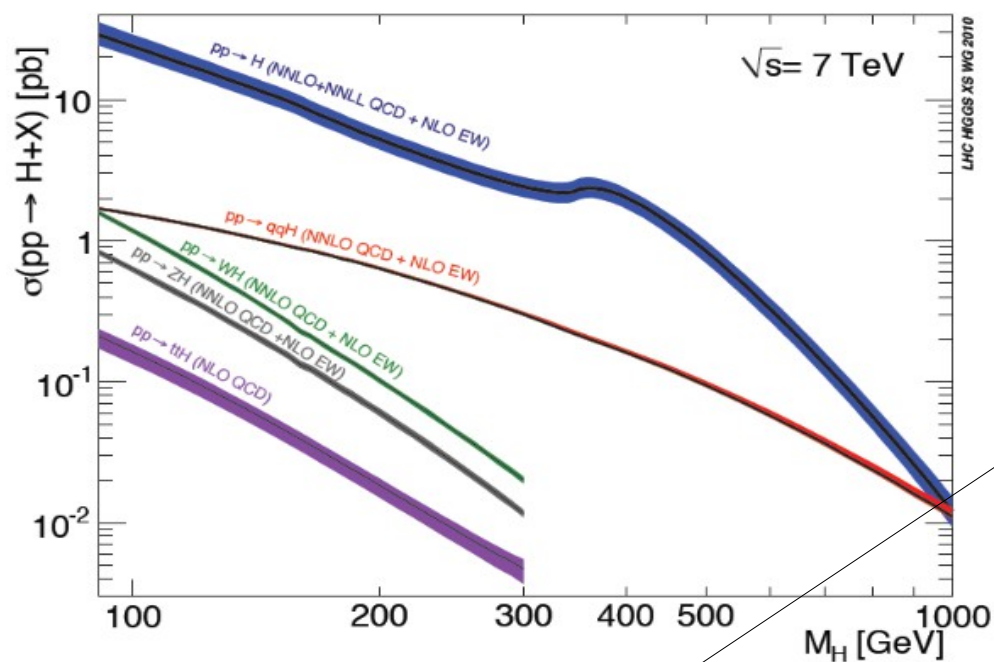
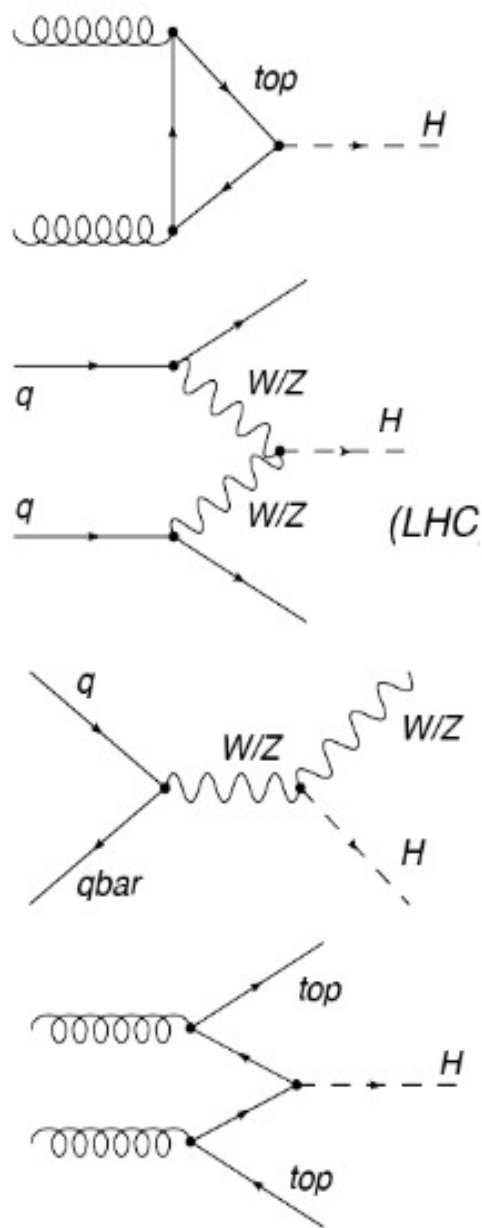
$$M_{\tilde{C}} = \begin{pmatrix} 0_{2 \times 2} & X_{2 \times 2}^T \\ X_{2 \times 2} & 0_{2 \times 2} \end{pmatrix}, \quad \text{with} \quad X_{2 \times 2} = \begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix}$$

$M_2$  Wino  
 $|\mu|$  Higgsino

$$\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & 1 \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

$$\begin{pmatrix} \chi_1^- \\ \chi_2^- \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & 1 \end{pmatrix} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix}$$

# Higgs production and decay at the LHC



Expect:

$\sim 400 \gamma\gamma$  events

$\sim 10 ZZ$  events